Powerful Data Recording Systems
for Diagnosis and Fatique Life Monitoring

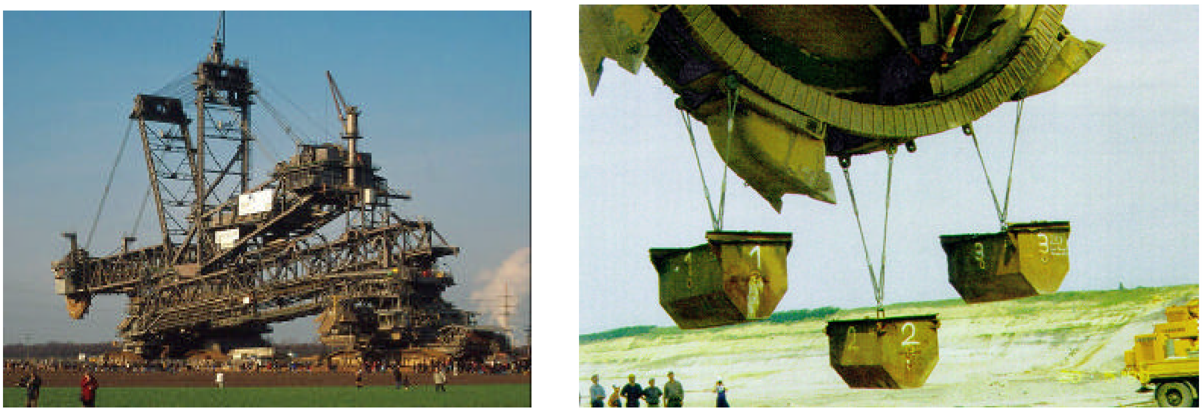
applied at Automobiles, Commercial Vehicles,
Heavy Machinery and Wind Turbines

Introduction

The design and construction of highly stressed and safety critical structures, such as landing gears, airframe structures, wind turbines, etc., is mainly based on assumptions regarding the expected operational stress loads, which are more or less substantiated depending on the particular application. Development trends towards constantly lighter structures together with increased demands for higher levels of safety, require the use of sophisticated methods to determine the operational, design and proof loads. A further complicating factor results from the varying stress loads and environmental conditions to which the structures can be exposed depending on their operational usage.

The design engineer is interested in measuring the actual stress conditions on existing, deployed structures, in order to estimate the future stress behaviour of new structures. In the absence of such experimental data, the anticipated damage or failure of a highly stressed component can be identified through regular maintenance – as is carried out on aircraft. Such a maintenance policy implies the possible risk of the maintenance interval being too long for severe stress situations. Such problems can be avoided – at reasonable cost – by monitoring the stress events and periodically comparing the measured data with the corresponding design limits to determine whether or not the component has already reached its approved rating.

For both tasks (i.e. the identification of actual stress on existing structures in support of new developments, and the monitoring of operational components to identify their fatigue life limits), the measurement of the actual load and stress data is essential. These data are usually recorded and subsequently analysed using appropriate methods – for example, the ‘Rainflow Counting’ method is suitable for fatigue life analysis. However, in view of the high number of measurement parameters that need to be monitored, the resulting data volume can become unmanageable unless appropriate on-line data reduction methods are employed.



Picture 1: Records of load and stress data at a lignite excavator, calibration

This paper describes a measuring system that has already been successfully used many times for both of the above two tasks. This system is the Aircraft Integrated Data Acquisition (AIDA) recorder, which is developed and manufactured by Swift GmbH of Germany based on the company's MICRO-II system. Typical AIDA and MICRO-II applications include:

- recording of stress loads on steel structures, e.g. lignite excavators (figure 1);
- recording of stress loads on motor cycles under customer ownership;
- monitoring of stress conditions on test vehicles;
- fatigue life monitoring of wind turbines (figure 2a);
- fatigue life monitoring of forging presses (figure 2b);
- fatigue life monitoring of airplanes and helicopters (figure 3).

Picture 2: Records of stress data at wind power plants and forging presses

Online Stress Monitoring at Helicopters

This section presents the technology and the functional characteristics of such a measuring system while describing its implementation on a fleet of helicopters. The project's objectives were:

- to extend the life time of the helicopters,
- to supervise the pilots,
- to organise an effective service and maintenance system, and
- to support in revising the load assumptions for design.

The presented project described the especially successful co-operation between the developer of the measuring facilities while applying intelligent software systems on the one hand and the complex requirements set out by the operator of the helicopters on the other hand.

Picture 3: Data logger in the helicopter

Within the context of their military tasks for the defence of Dutch territory, the Dutch Marine operates a fleet of ships and aircraft, which also comprise 22 helicopters of the type GK Westland LYNX SH-14D. As the military forces other NATO allies, the tasks and operating range of this helicopter type has been extended to also cover ex-territorial coastal areas. This required the installation of new equipment commensurate with the new tasks, such as radar warning receiver, forward looking infrared, global positioning system and chaff/flare.

The two changes called for the accurate supervision of the user profile and the resulting mechanical forces.

While taking a conservative approach and selecting the safety factors generously, the helicopter manufacturer designed the helicopters for a fatique life of 7000 operating hours. Due to the increased flight missions, the helicopters' annual operating times have now reached 350 to 400 hours. The accordingly reduced life time expectations would require the existing helicopters to be taken out of service before the successor model NH 90 will be operational.

The evaluation of a tragic accident – the crash of a German helicopter of same type after failure of the so called tie-bar, which is the semi-elastic tensile strained link between the rotor head and the rotor blade – added another argument for intensifying helicopter monitoring to extend the currently practised monitoring of selected helicopters to cover the whole fleet, i.e. each helicopter.

In the light of this discussion, the Dutch Marine initiated a comprehensive investigation with the target to introduce a careful analysis of every flight mission for each helicopter, linked to a "smart maintenance policy". The efforts were expected to be paid off in due course, given:

- the recorded forces/loads were smaller than the design forces/loads as assumed by the manufacturer for his life time calculations,
- accordingly prolonged maintenance intervals would save cost, and
- the delayed replacement of parts would save cost, too.

After respective preparatory works, the Dutch Marine carried out an evaluation of internationally available data recording systems of competing firms and ranked first the equipment manufactured by M/s SWIFT .

Supported by the National Aerospace Labaratory (NLR), the Marine and the industry collaborated in preparing a comprehensive specification which had to be met by the AIDA system.

Components of the AIDA System

The heart of the AIDA system is the "MICRO II" recorder. Being devised in modular design and mainly built in robust CMOS technique, it can accommodate up to 20 analogue measuring channels (including strain gauge conditioning), 16 digital measuring channels and 6 counter channels. The measuring range extends from 1mV to 10V. The programme storage uses a 256 k Byte – Flash-

EPROM. Data is stored in a buffered battery storage with a capacity of 4M Byte, that is extendable up to 16M Byte. PCMCIA memory cards can be used for the data transmission.

Despite its enormous capability the recorder's dimensions W x H x D = 112 x 172 x 195mm and weight of 3.8kg (MIL tested version) are small.

Part of the hardware of the AIDA system is a so called break-out box, which permits the direct access to the individual sensors and is used for testing and maintenance. If needed, it will be switched between the recorder and the sensors.

- 8 Parameter
- 17 Sensorsignale nutzbar
- > 30 Rechenoperationen fortlaufend
- 4 unterschiedliche Audio-Warnsignale
- Warnlampe im zentralen Kontrollpanel
- Eingebaute Selbstüberwachung

Picture 4: Main functions of the data logger

System control and the analysis and verification of the measuring data is carried out by a laptop computer with comfortable user menu. The user can set and adjust the measuring ranges, compensate the zero offset, start and stop measuring, transmit data to the earth station and display the data on the screen.

The so called earth station is a personal computer being used for the further processing of the measured data. In particular the PC serves for the evaluation of the measuring data, computation of used life time, registration of relevant events, e.g. exceeding of specified limits, visual display of measuring data and, as central storage for all data of the whole helicopter fleet. The earth station including the development of the comprehensive software is operated by the Dutch Marine.

Installation of the Recorder in the Helicopter

Prior to the recorder's installation on the helicopter, an extensive approval process was necessary. The approval of the recorder to current MIL standards was obtained in accordance with the jointly prepared specifications. On the German side, the "Güteprüfstelle der Bundeswehr (GPS)" has been actively involved in getting the recorder's certification and in keeping records on the production process in compliance with applicable quality control criteria.

After a strict selection process, the following 17 signals were selected for the monitoring in the end:

- Speed of the main rotor
- Speed of the low-pressure and high-pressure turbines of the two engines
- Velocity IAS
- Incidence
- Driving torque of both engines
- Strain control data in x- and y-direction at the sponsons
- Signal "landing gear loaded"
- Falling below of the specified limit for the height-finder radar
- 2 free measuring signals

Employed Software

The client had specified to design the storage capacity of the data recorder to cater for 100 flight hours continuous recording, i.e. without intermediate data transmission to the earth station. The large number of analogue channels with sampling frequencies of up to 2 kHz would have resulted in huge data quantities which would have absorbed the maximum storage capacity in few hours. It was decided, therefore, to resort to on-line classification and to continue with developing an intelligent software tailored to this application.

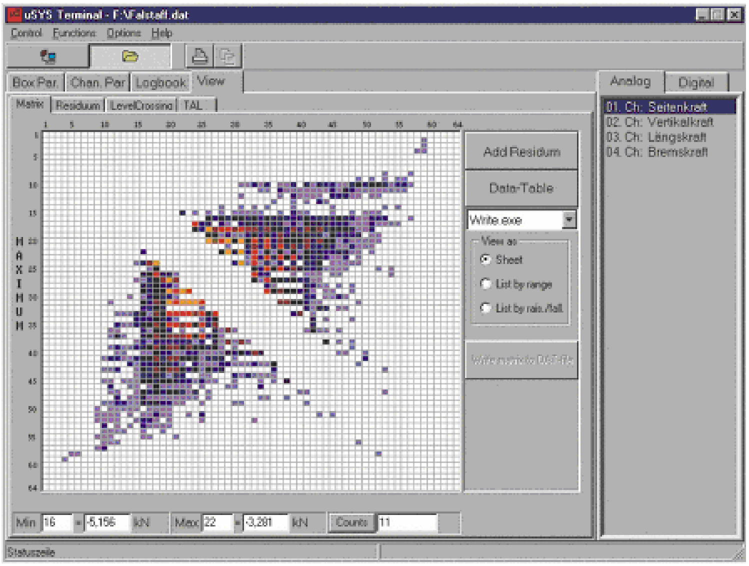
The "MICRO II" recorder has a large number of standard or optional evaluation algorithms at its disposal, that can also be employed in combination. The most relevant ones are addressed below:

RF - Rainflow

The RF algorithm reduces the data flow to the load peaks being relevant to the damage and further identifies those which are part of a closed hysteresis loop. These oscillations are classified and retained, e.g. in a 64x64 matrix. Such a matrix contains all information needed to calculate the deterioration. Within this context, the various methods as per Miner, or the extended concepts for consideration of medium voltage sensitivity as per W. Schütz. shall exemplary be mentioned.

The matrix also allows to subsequently generate a pattern of loads for at testing machine. The effect of such reconstructed load pattern corresponds to the previously recorded long-time test as to its mechanical stress on the tested object.

Meaningful results and small storage needs are the features which made the RF method to the preferred choice, when it comes to long time recording of operational stresses.



01. Ch: Seitenkraft
02. Ch: Vertikalkraft
03. Ch: Längskraft
04. Ch: Bremskraft

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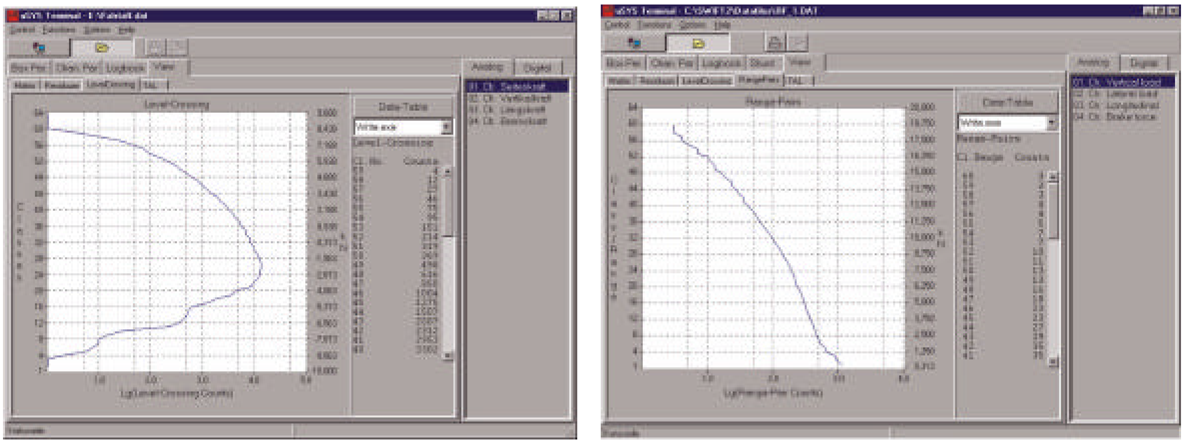
Min 16 = -5,156 kN
Max 22 = -3,281 kN
Counts 11

<u>Picture 5:</u> Rainflow ---- Record of peaks of closed hysteresis loops and clear presentation of results as matrix.
Semi-oscillations are temporarily stored and retained as residue.

Besides, the well known one-parametric methods as "LC-Level Crossings" and "RP-Rang Pair Count" can be generated from the RF matrix, too.

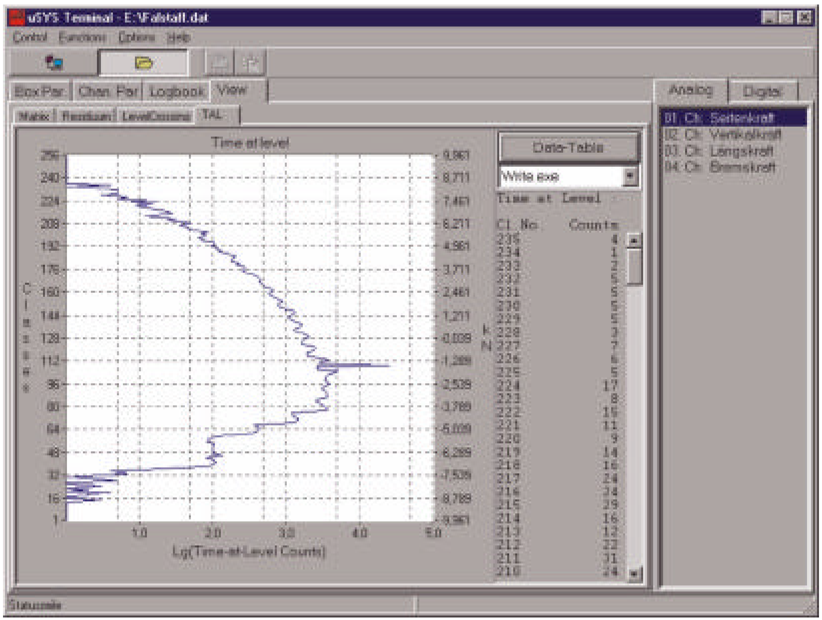


Picture 6: Level Crossings ---- Record of the crossing of previously determined class limits and clear presentation as cumulating frequency collective.
Range Pairs ---- Evaluation of range pairs, e.g. of identical load increase and decrease, presentation as cumulating frequency curve.

TAL - Time at Level

His method classifies the input signal for instance in 256 classes and determines the time span in which the input signal stayed within the respective classes. Typical examples are physical parameters as temperature, speed, velocity.

By reducing them to the time at level, a storage of a few kilobytes can easily accommodate the measured data recorded over years.



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Time at Level

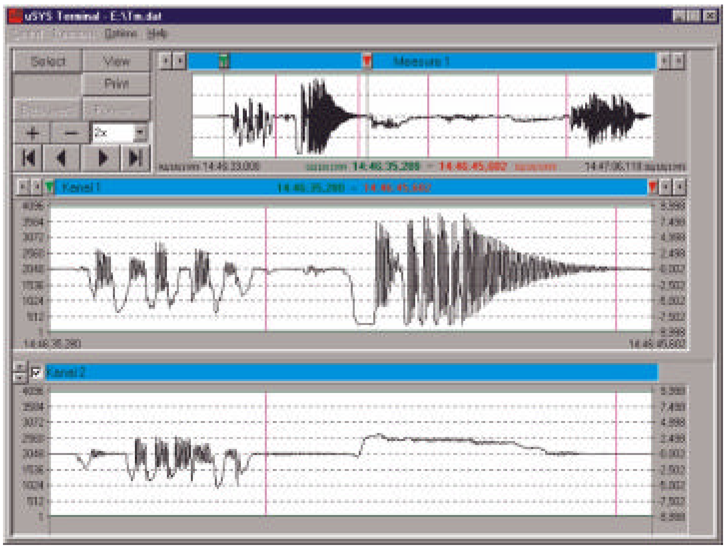
Cl. No      Counts
235              4
234              1
233              2
232              5
231              5
230              5
229              5
228              3
227              7
226              6
225              5
224             17
223              8
222             15
221             11
220              9
219             14
218             16
217             24
216             24
215             29
214             16
213             12
212             22
211             31
210             24
```

Picture 7: Time at Level ---- Adding up the time at level of a signal within determined class limits, presentation as cumulating collective.

TM - Transient Mode

All the above described methods have the same disadvantage, that the subsequent establishment of the credibility of a recorded signal is hardly possible or not at all. This can be a problem, if unexpectedly high peaks occur. This disadvantage can be overcome by combining the RF and TAL methods with a triggered recording of short time series. In addition to the activated counting methods, the actual signal progression will be simultaneously recorded, if the signal exceeds the predetermined limit. The limit can be individually defined for each channel, in order to keep the resulting data quantity within reasonable limits.

By adjusting the pre-trigger and post-trigger times, the history and the decaying process of the signal can be recorded, too. This enables the later evaluation of the signal progression beyond the set trigger times. The later evaluation of the signal progression will answer in most cases, whether a signal progression appears credible or was caused by a disturbance. This feature is supplemented by the optional mutual triggering of free selectable channels. It enables simultaneous recording of the main triggered event together with the signal progression of other channels, which can provide further valuable information.



Picture 8: Transient Mode with Trigger. Presentation as progression of amplitudes.

SQTMS – Sequential Peaks and Troughs with Master / Slave

This method is similar to the classical time series method. The SQTMS method reduces the measured quantity to the stress relevant load peaks and records them together with the pertaining time information. The adjustable amplitude suppression ensures that marginal stress reversals and noise are filtered.

Since the volume of the recorded data only depends on the signal frequency, the sampling rate can be selected very high, to best detect the signal extremes as to time and amplitude.

The recorded time information enables to subsequently visualise several time-wise correlated channels. This option can be further extended by employing slave channels. The momentary value of the slave channels is automatically retained, if a signal peak is recognised in the master channel.

As mentioned before, the data volume generated by SQTMS is dependent on the signal only. For example, a 4 Megabyte memory stores one million stress reversals, that is close to the continuous working strength.

Since all load peaks are recorded, the SQTMS data can be used to subsequently generate a RF matrix, which, hence constitutes the interface to all current methods for analysis of working strength.

Picture 9: Sequential Extremes with Time and Master/Slave Function. Presented as amplitude progression with master and slave channel.

The Application of the Evaluation Methods with the AIDA Recorder

The SQTMS and LC methods are employed for the evaluation of the speed of the main rotor and the engine rotors as well as the strain control data at the sponsons. The criterion is the significant reduction of the data volume to be stored while all information is retained for the subsequent computation of used life time.

Besides recording the load spectra, the recorder carries out numerous supervision tasks and initiates acoustic or optic warnings to the pilots in the cockpit. A total of 36 processes are controlled, i.a. for exceeding or falling below the specified speed limits of the main rotor including recording the time period and frequency of occurrence, or the signal for “landing gear is loaded”, also with duration and frequency.

In addition the recorder is provided with various self-diagnosis functions.

Für Selbstüberwachung des Recorders werden folgende Hauptparameter herangezogen:

1. Schalter “Fahrwerk belastet”
2. Drehzahlen der Triebwerke
3. Test des Recorder-internen Speichers
4. Echtzeituhr zur Überwachung der zentralen Prozessoreinheit des Recorders
5. Speicherüberlauf

Die Kombination der Werte dieser Parameter werden verwendet für:

1. Sofortige Anzeige für den Piloten, wenn der Recorder keine Warnung bei Rotorüberdrehzahl abgibt.

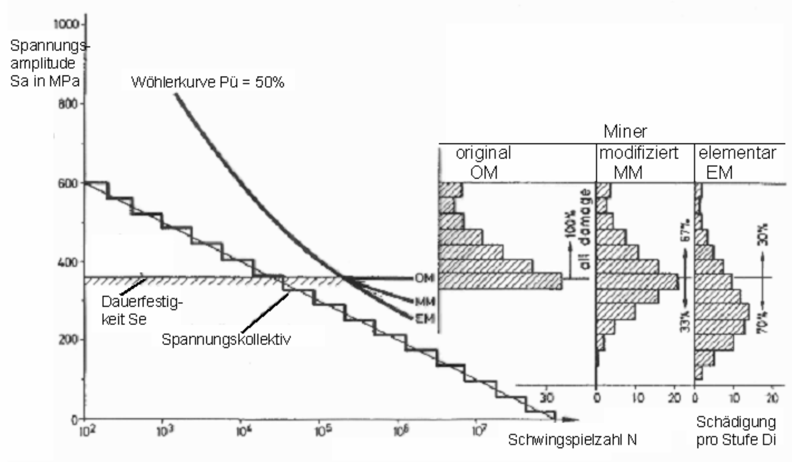
2. Bericht für der Wartungspersonal, um das System zu überprüfen

Picture 10: Supervisory Functions

Data Reading and Evaluation

At regular intervals, e.g. once a month, the maintenance personnel read the data by means of laptop and PC card and transmit them to the PC of the earth station for further processing.

This processing involves the computing of accumulated deterioration by means of special software. This serves for the identification of the occurred operational stresses and strains and allows to evaluate, in relative terms, the deterioration versus the design load collectives. It is important to note, that the calculation of relative deterioration can be performed with real stress-number curves (“Wöhler” curves). Thus, the evaluation of the deteriorating effect of the numerous small oscillations that occur during the operation are based on rather realistic parameters.



Picture 11: Evaluation of deterioration with recorded and online reduced data

Picture 11 displays the influence of different computations of accumulated deterioration with “Wöhler” curves, while assuming a definite fatique strength (as per Miner). However, this would not reflect the virtual operational deterioration of the components and imply great risks. On the other hand, the “Wöhler” curve can also be extrapolated with the same gradient to the area of higher oscillations (as per Miner), which would correspond to the very conservative approach ignoring any existing strength reserves. Today’s widely accepted approach is based on the assumed extrapolation of the “Wöhler” curve with a smaller gradient to the definite fatique area (modified as per Haibach).

Results

After a sufficient trial operation period, the AIDA system started normal operation as part of the Dutch Marine’s “Smart Maintenance Policy” early in 1999.

The main achievements:

- The annual maintenance cost for the whole helicopter fleet was reduced by approx. 2.5 Mio $.
- The intervals for replacing engine parts could be prolonged. The cost for the periodical basic overhaul could be reduced by up to 25%.
- The safety of flight operations was increased, since violation of the rotor speed limits are easily detected (affects the pilots’ discipline?).
- The load assumptions for fatique life computation could be revised, after the parameter was changed from flight hours to measured load reversal.
- The data bank contains the real stress behaviour of the whole helicopter fleet which may be used by the Marine to optimise the operational control of flight missions.

Future Outlook

The success of the AIDA system in terms of

- increased safety,
- saved maintenance cost, and
- extended life time and flight time

for the LYNX helicopters is so convincing, that other operators become interested in this system. The AIDA system is already used by the Brazilian and Dutch Marine with comparable advantages. The Danish Marine have commenced with respective pre-investigations. After successful trial operation on two pilot schemes, the German Marine have equipped all their Sea Lynx with AIDA recorder systems.

Beside these military applications, the derived industrial version has been successfully employed by many users, e.g. in the aircraft industry, the automobile and motor cycle industry, the mechanical engineering industry as well as of manufacturers of tailor-made machines, e.g. cranes and excavators.

The hardware and software of the recorder is subject to permanent further development in line with new clients' terms of reference. Thus, the recorder's range of applications is constantly enlarged and becomes interesting to an even wider user group.